論　文　の　要　旨

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論 文 題 目　Stability analysis of non-neutral ion plasma in a linear Paul trap and its application to particle beam dynamics
（線形ポールトラップ中に捕獲された非中性イオンプラズマの安定性解析とその粒子ビーム力学への応用）

It is extremely important to have clear understanding of resonant beam instability for a better design of a modern particle accelerator. For this purpose, we have developed "Simulator of Particle Orbit Dynamics" (S-POD) that enables us to clarify various beam-dynamics issues without relying on large-scale machines. This unique tabletop experiment is based on an isomorphism between non-neutral plasmas in a compact Paul trap and charged-particle beams in a linear focusing channel. S-POD is particularly useful in exploring collective effects in intense hadron beams. This thesis addresses systematic Particle-In-Cell (PIC) simulations performed to explain experimental data from S-POD. A possible design of a novel multipole ion trap is also proposed for a future experiment study of nonlinear beam dynamics. The contents of the present work include the following three main subjects.

(1) Collective resonance instabilities and its lattice-structure dependence.
Almost all modern particle accelerator systems exploit the principle of strong focusing. Each accelerator has a unique lattice structure optimized for a certain experimental purpose. We here focus on several standard alternating-gradient (AG) lattices such as doublet, triplet, FDDF, etc. These AG focusing potentials can readily be reproduced in S-POD. We employ the PIC code "Warp" to support S-POD experiments. A number of systematic multi-particle simulations are carried out to explain the experimentally observed collective instabilities induced by the external AG driving forces. The excitation of extra resonance bands due to lattice symmetry breaking is also studied in detail. We confirm that PIC simulation results are consistent to experimental observations as well as theoretical predictions from the linearized Vlasov analysis.

(2) Theoretical and simulation study of resonance crossing.
Considerable theoretical and experimental efforts have recently been devoted to design studies of non-scaling fixed-field alternating gradient (ns-FFAG) accelerators are for various purposes including hadron therapy, accelerator-driven reactor systems, a muon collider, and a neutrino factory. In this type of machines, the bare betatron tunes keep decreasing rapidly while the beam is accelerated by radio-frequency cavities. It is almost inevitable for the operating point to cross resonance stop bands, some of which may be quite dangerous.

In this subject, we first investigate fundamental features of collective resonance crossing with the Warp code and compare simulation results with experimental observations in S-POD. A simple scaling law is derived for a quick estimate of the emittance growth caused by crossing of an intrinsic space-charge-driven resonance. We then proceed to an extensive study of integer resonance crossing. A dipole driving field was intentionally added in recent S-POD experiments to excite integer resonances. We show that experimental results can be well explained by Warp simulations and predictions from analytic models. The rate of ion losses after consecutive crossing of integer resonance bands is evaluated as a function of crossing speed and the relative initial phase of dipole driving forces. An effect of nonlinear external fields, practically unavoidable due to finite mechanical imperfections and other sources, is also briefly studied.

(3) A modified Paul trap for study of nonlinear beam-dynamics studies.

Any particle accelerators include weak nonlinear fields generated by mechanical errors and even nonlinear multipole magnets for beam orbit correction. Nonlinear error fields are also present in a Paul ion trap, enhancing high-order resonances under certain conditions. The main source of nonlinearity in a regular trap is the misalignments of the quadrupole rods, which means that the strength and time structure of the nonlinear fields cannot be controlled independently of the linear focusing field.

In this subject, we propose a multipole ion trap that enables us to conduct a systematic experimental study of nonlinear effects in particle accelerators. The proposed modified Paul trap has four extra electrodes in between the regular quadrupole rods. It is possible to control low order nonlinearities in the plasma confinement potential by applying proper rf voltages to these electrodes. Simple scaling laws are derived for a quick estimation of low-order nonlinear field strengths. We perform test numerical simulations to verify the controllability of sextupole and octupole resonances in the modified trap.